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Flow Pattern in Compound Channel with Floodplain Double Groyne

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Abstract

The results of an experimental study and velocity analysis of the flow characteristics in the vicinity of a floodplain with two rows of permeable/impermeable groynes in compound channels with one and two floodplains are presented. A 60% permeable groyne model with three different lengths relative to the floodplain width was used. The results showed that double groyne could be considered as one groyne (one block) for aspect ratio $S_r < 2$ (S_r = distance between two successive groynes/groyne length). When $S_r > 2$, each groyne started to act independently. The velocity reduction was more than 45-52% of the floodplain's approach velocity compared with 30-35% in the case of a single groyne. The significant velocity reduction was located at a distance 1.5-2 times the groyne length downstream of the single or the double groynes. Generally, the maximum velocities in the main channel ranged from 1.1 to 1.35 times the original approaching velocity. The effective groyne relative length and aspect ratio should not to be more than 0.5 and 2, respectively.

Key words: Compound channel; double groynes; flow pattern; permeable groyne; PIV.

1. Introduction

Groynes are hydraulic structures used to protect river banks from erosion and maintain water levels by deflecting the flow direction. In addition, the natural banks formed by groynes are beneficial to

river ecosystems. Impermeable groynes are generally constructed using local rocks, gravel, or gabions, whereas permeable groynes consist of rows of piles, bamboo, or timbers. Groynes may be built as a single structure, i.e., a single groyne, or as a series of groynes built in rows along one or both river sides, i.e., as a groyne field (Alvarez 1989; Uijttewaal *et al.* 2001; Ettema and Muste 2004; Uijttewaal 2005; Yeo *et al.* 2005; Gu and Ikeda 2008; Muraoka *et al.* 2008; Teraguchi *et al.* 2008; Ahmed *et al.* 2010, 2011; Mostafa *et al.* 2013).

River floodplain groynes play important roles in providing high flood attenuation and protection works, especially in rivers with large and complex floodplains. Impermeable groynes, transverse levees, and bridge embankments are considered to serve as contractions along the stream-wise flow direction. The flow structures around groynes on river floodplains are presumably different from those in single main channels. The flow through a permeable groyne partly penetrates the structure with less resistance such that the downstream velocity is effectively reduced (Yeo *et al.* 2005; Jong and Tominaga 2008; Ahmed *et al.* 2010, 2011; Kang *et al.* 2011). Furthermore, designing parameters depending on the flow analysis are necessary in selecting the most appropriate groyne design. Nonetheless, permeable groynes have the advantages of excellent stability and relatively easy maintenance (Yeo *et al.* 2005; Kang *et al.* 2011).

In the junction region between the main channel and the floodplains of compound channel, the characteristics of compound open-channel flows were identified, whereas in the region near the sidewall of the main channel, the characteristics of rectangular open-channel flows were observed. Strong and inclined secondary currents, which were associated with a pair of longitudinal vortices and affected the primary mean velocity field, were generated (Tominaga and Nezu, 1991).

In the mixing layer between the groyne field and the river, two-dimensional large coherent structures (2DLCS) were observed, and these flow structures controlled the majority of mixing processes associated with the main river (Weitbrecht *et al.* 2008). The groynes on the floodplain deflected the main flow and produced 3-D flow structures around the groynes. These local flow

features affected the main-channel flow and generated strong secondary flows in the main channel (Jong and Tominaga 2008). Sukhodolov (2014) reported that Westrich in 1978 introduced the aspect ratio S_r ($S_r = \text{distance between two successive groynes} / \text{groyne length}$) as a quantitative criterion for circulation patterns in a groyne under emerged conditions. The critical value of the aspect ratio $S_r = 2$ delimited conditions for the formation of either multiple ($S_r > 2$) or single ($S_r < 2$) circulation systems.

Around floodplain single groyne, when the flow occurred near the groyne a significant momentum flux related to mass exchange between the subsections could be observed. In the floodplain, due to the turbulent exchange, the momentum transfer was due to the mass exchange and was several orders of magnitude larger than that due to turbulent exchange. Additionally, the momentum transfer was of the same order of magnitude as the friction on solid walls, regardless of the relative floodplain depth or the groyne length. In the main channel, the solid wall friction was equal to or greater than the momentum transfer (Peltier *et al.* 2009, Baba *et al.* 2010).

Ahmed *et al.* (2010) investigated a compound channel with two symmetrical floodplains with single and double impermeable groynes having three relative lengths on one floodplain side. The authors concluded that the groyne length must be kept less than half the floodplain width. In addition, the effective aspect ratio of two series of impermeable groynes ranged from 3 to 4. In another study, Ahmed *et al.* (2011) simulated the flow in the Arakawa River network, Japan, which is flanked by one or two large floodplains with impermeable groynes and bridge embankments. The floodplain width in the Arakawa River was in some cases more than 10-times the main river width. The groyne length ranged from 0.16 to 0.81 of the floodplain width. The average reduction in the flood discharge using floodplain groynes was approximately 7–15%, and floodplain groynes were found more effective in flood attenuation and protection works.

In some rivers with wide floodplains, large-scale permeable and impermeable groyne systems have widely been introduced and used in one or more works of flood attenuation, protection of river

banks, safety of downstream areas, and navigation (Ahmed *et al.* 2010, 2011). Consequently, the present laboratory-scale study presents more quantitative and extensive analyses of the flow around floodplain permeable groynes arranged in series. The objectives of the present study are: 1) to investigate the effects of large-scale floodplain double permeable groynes (series of two groynes) on the compound channel flow velocity and structure, 2) to evaluate and investigate the advantages and disadvantages of using floodplain permeable groynes in a sequence (double) arrangement instead of impermeable ones.

To achieve these objectives, the flow structure in the vicinity of floodplain double permeable groyne and main channel was investigated in the two dimensions, the longitudinal and transverse direction, using the PIV technique in addition to performing flow velocity measurements using an Acoustic Doppler Velocimeter (ADV). Influences of the floodplain double permeable/impermeable groyne relative length and aspect ratio on the flow patterns and structure in both the main channel and the groyne domains were investigated. Permeable groyne models with permeability 60% and three relative lengths were used.

2. Study methods

Three series of experiments were conducted (Table 1). The first series, Series-I, was conducted to investigate the effects of floodplain permeable groynes in a double arrangement on flow patterns. The rectangular flume section was converted to a Perspex-acrylic unsymmetrical compound channel section having a main channel and one floodplain with fixed and smooth beds with the same hydraulic conditions. The longitudinal velocity U and lateral velocity V were measured in the horizontal plane HP, which was located at a depth of $0.25h$ from the floodplain bed. The flow velocity components were measured using an Acoustic Doppler Velocimeter (ADV) (16 MHz MicroADV, Sontek, with a sampling frequency of 20 Hz). At each point, the mean velocities U and V were obtained by averaging the velocity readings of the Velocimeter.

The second series of experiments, Series-II, was conducted using the Particle Image Velocimetry (PIV) technique. The flume used had the same width and depth as that used in series-I, whereas its overall length was 11 *m* with a 7.5 *m* transparent test section length. The test section was located 4 *m* downstream of the flume entrance. To visualize the flow, nylon resin particles measuring 20 μm in diameter and 1.02 in specific weight and a green laser light sheet measuring approximately 3 *mm* thickness were used.

In both series-I and series-II, the permeable groynes models were made of glass piles with a cross-sectional diameter of 0.50 *cm* and permeability of 60%. Groyne models with three relative lengths, $L_r = 0.5, 0.75$, and 1 (where, $L_r = \text{groyne length } L_g / \text{floodplain width } b_f$), and placed perpendicular to the longitudinal flow direction were used. In case of double groyne model, the groyne relative length was the same for each groyne. In series-II, six cases were considered to study the effect of the groyne relative length and the aspect ratio S_r on flow patterns and velocities. The flow transverse and longitudinal velocity distribution were measured and plotted at six cross-sections along the channel (Table 2).

Other experiments, Series-III, were conducted using two identical impermeable groynes installed perpendicularly on the floodplains of symmetrical compound channel with two large floodplains with relative width =2.0 (Table 1). The flume was 0.50 *m* in depth and width and 15 *m* in length. The cross-section of the flume was converted to a wooden symmetrical compound channel section consisting of a main channel and two symmetrical floodplains. The flow velocities at the horizontal plane at the floodplain mid-water depth and at the vertical plane at the main channel centreline were measured by using electromagnetic velocity meter (EMV) (type of main amplifier: VM-2000; type of sensor: VMT2-200-04P, Kenek Company, Ltd). The Froude number was almost kept constant that ranged from 0.26 to 0.30 (Table 1).

3. Results and discussion

3.1 Effects of the double impermeable groyne.

In the present study, for better investigation and clarification effects of the large-scale floodplain double impermeable groynes, impermeable groynes models with relative lengths 0.75 and 1 were chosen. The impermeable groyne with relative length of 0.5 had little effect on the flow pattern, structure, and velocity reduction between groynes (Ahmed *et al.* 2010; Mostafa *et al.* 2013). The flow deflected and moved toward the main channel, increasing the velocity near the bed and decreasing it near the surface, and the maximum relative velocity increased as the relative length of the double-sided impermeable groyne increased (Series-III, Figs. 1 and 2). This behaviour generated spiral vortices in the main channel downstream of the groynes. The maximum relative velocity in the horizontal plane HP was 2 and 2.8 times the approach velocity while in the vertical plane VP was 2.5 and 3 times when L_r was 0.75 and 1, respectively. The reduction of the floodplain velocity was more strongly affected by the upstream groyne than the downstream one. The two groynes acted separately and independently as the aspect ratio increased and exceeded 6. The effective aspect ratio was in the range of 2-4. The tip velocity increased with the groyne relative length; ranged from 1.5 to 2 and from 2 to 2.5 times the approach velocity for $L_r = 0.75$ and 1, respectively. Most of the increase in the tip velocity occurred in the middle and lower regions of the main channel. The impermeable groyne relative length should be less than 0.5 and the aspect ratio can be 4 to avoid scouring destructive activities in both the main channel and floodplains. Those results are in agreement with Ahmed *et al.* (2010) for case of a series of two identical impermeable groynes with $L_r = 0.75$ and 1 on one side of a symmetrical compound channel with a floodplain relative width = 2. Both the groyne relative length L_r and the aspect ratio S_r greatly affected the flow structure, pattern, and velocity. The double groyne could be considered as one groyne (one block) for $S_r < 2$. When $S_r > 2$, each groyne started to act independently of the other. The effective distance S_r

between double groynes was from 3 to 4 times the groyne length. There was an increase in the longitudinal relative velocity at the main channel centreline on the vertical plane as S_r increased to 4. Greater S_r caused a reduction in the longitudinal relative velocity after S_r exceeded this value. These values of S_r are in agreement with those obtained by Sukhodolov (2014). Also, at the vertical interface between the main channel and floodplains, a significant momentum flux related to the mass exchange between the floodplain and main channel was observed by Peltier *et al.* (2009) but with different values because of the channel geometry.

3.2 Effects of the double permeable groyne relative length.

Fig 3 shows the cross-sectional distribution maps of the flow longitudinal time-averaged velocities $u(y, z)$, and Fig. 4 presents the transverse time-averaged velocities $v(y, z)$ for the permeable groynes with three values of $L_r = 0.5, 0.75$, and 1. The results presented in these figures are for a constant $S_r = 1$ (Cases A, B and C) compared with the case of a channel with no groyne. The positive sign means that the flow is toward the floodplain, and the negative sign means the flow is toward the main channel.

The flow patterns around groynes with $L_r = 0.5$ were different from the patterns around groynes with a relative length $L_r = 1$ which mainly occurred in the floodplain area. The velocity gradient in the floodplain area was rapid in the case of $L_r = 0.5$ compared to that in which $L_r = 1$ in both the longitudinal and the transverse directions. For smaller groynes with $L_r = 0.5$, the velocities increased near the groyne tip and on the right side of the floodplain and decreased in the region between the two groynes and also on the downstream side. This behaviour occurred due to the effect of the small relative length of the groyne.

In the case of a compound channel with no groyne, as discussed by Tominaga *et al.* (1991), inclined secondary currents are generated from the junction edge (the interface edge between the floodplain and the main channel) toward the free surface of the compound open-channel flow. On both sides of

the inclined up-flow (the floodplain side and main channel side), pairs of outlines of secondary currents are identified. These currents can be regarded as "longitudinal vortices". The vortex located on the floodplain side is called the "floodplain vortex", whereas the vortex on the main channel side is called the "main-channel vortex". Both vortices reached the free surface and covered the interface region. In the sidewall region of the main channel, a horizontal vortex from the side wall to the centre of the main channel appeared at the free surface, forming a longitudinal vortex called the "free surface vortex". The flow currents in the area near the banks were in the direction toward the floodplain bank. Upstream of the groynes model, at sec. I, the floodplain flow moved toward the main channel, starting from the midpoint of the groyne, and was strongly deflected at the interface between the main channel and the floodplain (Fig. 4). As the groyne relative length increased, the so-called "floodplain vortex" disappeared. The flow secondary currents in the region from the groyne mid-point to the floodplain bank were the same as when there was no groyne in place. In the main channel, the effect of the groyne relative length was strong, and the so-called "main-channel vortex" vanished when $L_r = 1$, whereas it appeared when $L_r = 0.75$ and 0.5 . In the sidewall region of the main channel, the free surface vortex was very weak only in the case in which $L_r = 1$. The structure of the secondary currents was more affected by the groyne length than the geometry of the channel.

Downstream of the first groyne and also at the mid-distance between the two groynes, the characteristics and directions of the secondary flow in the main channel were the same as those on the upstream side of the groynes. The flow velocity decreased in the floodplain area and increased in the main channel, and the main-channel vortex appeared again when $L_{\frac{1}{2}} = 1$. In the region close to the second groyne, the secondary currents were more strongly deflected toward the main channel than upstream of the two-groyne model. Increasing the groyne relative length caused further velocity deflection in the region between the two groynes and also reduced the floodplain flow velocities near the banks. Downstream of the two-groyne model, at sec. V, the secondary currents at the

interface were strong for $L_r = 0.75$ and 1. The positive velocities near the floodplain banks disappeared because the flow currents were weakened and completely directed toward the main channel. The main-channel vortices still existed. The groyne permeability caused a reduction in the momentum flux at the vertical interface between the main channel and floodplains and the momentum flux related to the mass exchange between the main channel and floodplain.

3.3 Effects of the double permeable groyne aspect ratio.

For the region upstream of the double permeable groins model, there were no obvious effects of the aspect ratio, whereas the flow velocities and patterns between the two groins and downstream of the groins were affected by the aspect ratio (Figs. 5 and 6). For $Sr = 7$ and 8.5, respectively, the transverse velocity (v) downstream of the second groin deviated to the floodplain because the flow was trying to reach an equilibrium state (Fig. 7-f and 7-g)). The longitudinal velocity gradient was greater on the downstream side of the second groin than on the upstream side. This discrepancy is attributed to both the transverse flow and the aspect ratio, and was a result of the combined effect of the two permeable groins and the geometry of the compound channel. In all cases, the flow velocity in the main channel increased, and the maximum velocities occurred near the right bank (the right vertical side of the main channel). As the aspect ratio increased, the region of maximum velocities extended further downstream of the second groin.

At sections I, II, and III, the main-channel secondary currents were almost the same as those in cases A, D, E, and F, where the main channel and the free-surface-vortices existed, but they were stronger than the vortices for the case of no groyne (Figs. 8 and 9). The floodplain vortex disappeared. In the region between the two groynes, the direction of the floodplain secondary currents was toward the main channel, and the velocity increased as the aspect ratio increased. This behaviour occurred because of the second groyne's effect on the flow field between the two groynes. The effect of the aspect ratio on the flow structure appeared in the vicinity of the second groyne, on both the

upstream and downstream sides of sections IV, V, and VI. Comparing cases E and F with cases A and D, the groyne tip velocity was stronger, and the maximum negative velocity occurred near the bottom of the second groyne. The secondary currents in the floodplain area were directed toward the main channel. In the main channel, the secondary currents, in the direction toward the floodplain, for $S_r = 3$ and 4, increased and extended to the entire width of the main channel, where the maximum velocities were near the interface between the floodplain and the channel and at the flow surface.

In the case of $S_r = 1$, the effect of the two sequential groynes was similar to that in the case of a single one because the flow between the two groynes was not affected by the second (downstream) groyne. Accordingly, the two groynes with $S_r=1$ could be considered a single groyne with two rows of identical groynes. Downstream of the double groynes, the velocity decreased to a greater extent than in the case of a single groyne, especially in the floodplain area. The velocity reduction in the floodplain was 45-52% of the approach velocity, compared with 30-35% in the case of a single groyne (Fig. 10a). The greatest velocity reduction occurred at a relative distance of 1.5-2 downstream of the two groynes.

For cases in which $S_r > 1$, the effect upstream of the groyne was greater than that downstream as the longitudinal velocity deviated further and decreased. As the aspect ratio increased, the velocity gradient downstream of the second groyne increased. Downstream of the groyne model, for $S_r > 4$, the reduction in the floodplain velocity was slightly different for each groyne. In other words, each groyne behaved independently of the other groyne (Fig. 10). In the region between the two groynes, the velocities decreased but at smaller rates than those on the upstream side. In addition, the rate of the velocity reduction increased as the aspect ratio increased.

4. Conclusions

This study analysed and investigated the effects of floodplain double permeable groynes on the flow structure, patterns, and velocities in the corresponding groyne field and in both the floodplain and main-channel regions.

The following conclusions can be drawn from this study:

- The preferred relative length of the floodplain groynes that is useful for velocity reduction and bank protection is no more than 0.5 of the floodplain total width;
- The floodplain width relative to the main channel width has a great effects on the flow structure on both the main channel and the floodplain especially in case of floodplain impermeable groynes with relative length greater than 0.5;
- Generally, in the case of permeable groynes, the maximum velocities in the main channel were in the range of 1.1 to 1.35 times their approach velocities, whereas in the case of the impermeable groynes, the values could reach 2-3 times the approach velocities;
- Upstream of the double permeable groynes, as the groyne relative length increased, the so-called "floodplain vortex," disappeared. The flow secondary currents in the region from the groyne mid-length to the bank were the same as those for the case in which there was no groyne. In the main channel, the effect of the groyne relative length was observed, and the so-called "main-channel vortex" vanished when $L_r = 1$, whereas it was present when $L_r = 0.75$ and 0.5;
- The effect of the aspect ratio appeared at the mid-distance between the two groynes and near the downstream groyne. As the aspect ratio increased, the region downstream of the groyne tip may be more exposed to scouring activities;
- In the floodplain field, the longitudinal velocity decreased as the permeable groyne relative length increased; and

- The effect of the aspect ratio on the flow pattern was the same as that of the relative length but with smaller values of mean velocity.

Within the limitations of the present research and for design purposes, it is recommended that the relative length and aspect ratio of a groyne to be 0.5 and 2, respectively, and the permeability would be about 60%. These values had little effect on the main-channel flow and helped in providing bank protection. These effects are attributed to the lower scouring activity associated with these values of groyne permeability, relative length, and aspect ratio.

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Figure captions

Fig 1. Floodplain double identical groynes in a symmetrical compound channel with $L_r=0.75$. a) Distribution maps of the longitudinal velocity in HP and (b and c) maximum and minimum relative longitudinal velocity in HP and VP, respectively.

Fig 2. Floodplain double identical groynes in a symmetrical compound channel with $L_r=1$. a) Distribution maps of the longitudinal velocity in HP, (b and c) maximum and minimum relative longitudinal velocity in HP and VP, respectively, and d) profiles of the flow-wise velocity “ \underline{u} ” in the plane VP upstream and downstream groynes.

Fig 3. Floodplain double permeable groynes in a compound channel with one floodplain. Cross-sectional distribution maps of the longitudinal velocity (u) at different positions, Cases A, B, and C. (Where, $L_r = 0.5$, 0.75 , 1 and $S_r = 1$).

Fig 4. Floodplain double permeable groynes in a compound channel with one floodplain. Cross-sectional distributions maps of the transverse velocity (v) at different positions, Cases A, B, and C. (where $L_r = 0.5$, 0.75 , and 1 , and $S_r = 1$).

Fig 5. Floodplain permeable groynes in compound channel with one floodplain, distribution maps of the longitudinal velocity (u) for (a) single groyne and (b, c, d, e, f and g) double groynes with $S_r = 1, 2, 3, 5.67, 7$ and 8.5 , respectively ($L_r = 1.0$).

Fig 6. Floodplain permeable groynes in compound channel with one floodplain, distribution maps of the longitudinal velocity (u) for (a) single groyne and (b, c and d) double groynes with $S_r = 2, 4$ and 6 , respectively ($L_r = 0.5$).

Fig 7. Floodplain permeable groynes in compound channel with one floodplain, distribution maps of the transverse velocity (v) for (a) single groyne and (b, c, d, e, f and g) double groynes with $S_r = 1.0, 2.0, 3.0, 5.67, 7.0$ and 8.5 , respectively, ($L_r = 1.0$).

Fig 8. Floodplain double permeable groynes in compound channel with one floodplain, cross-sectional distribution maps of the longitudinal velocity (u) at different positions for Cases A, D, E and F (where $S_r = 1, 2, 3$ and 4 , respectively, and $L_r = 0.5$).

Fig 9. Floodplain double permeable groynes in compound channel with one floodplain, cross-sectional distribution maps of the transverse velocity (v) at different positions, Cases A, D, E and F (where $S_r = 1, 2, 3$ and 4 , respectively, and $L_r = 0.5$).

Fig 10. Floodplain double permeable groynes in compound channel with one floodplain, the relationship between the relative floodplain mean longitudinal velocity (u_f) and the relative longitudinal distance $X_r = X/b_f$ (where, a) $L_r = 1.0$ and b) $L_r = 0.5$).



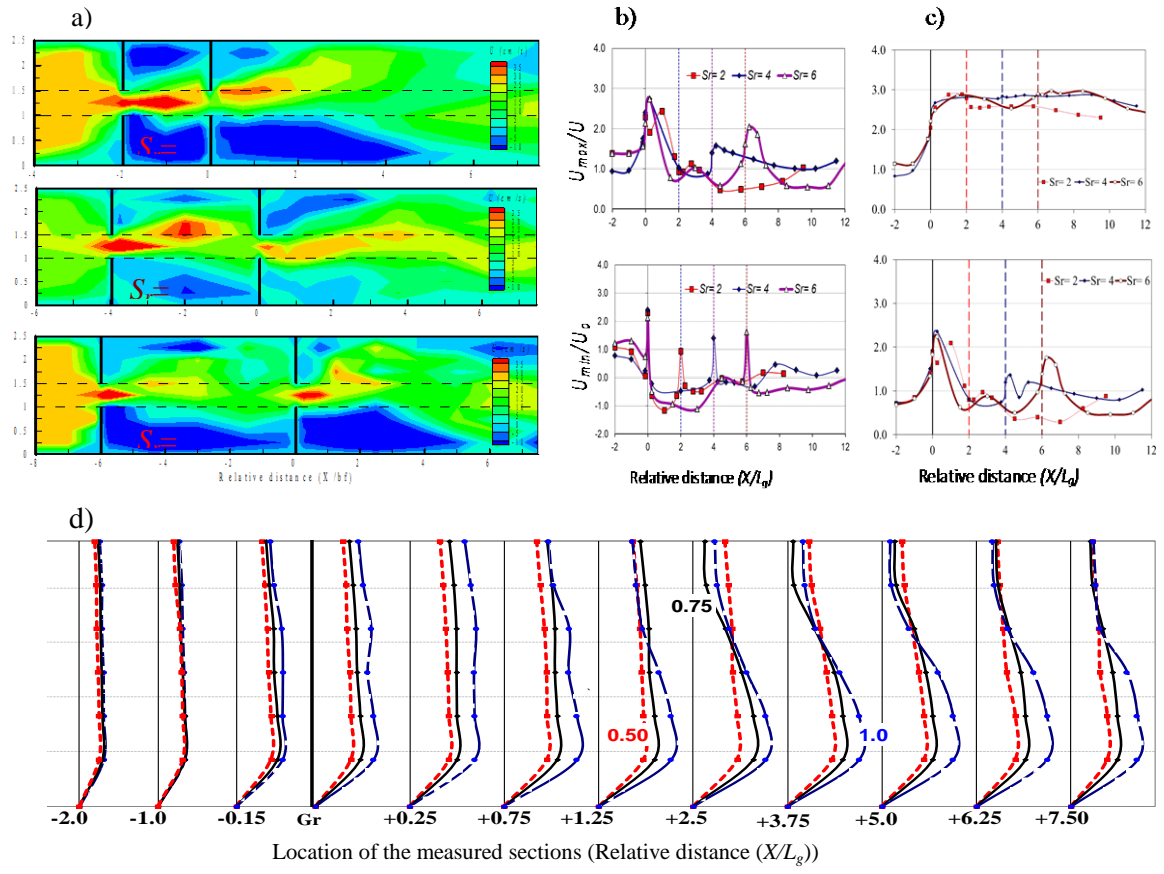


Fig 2

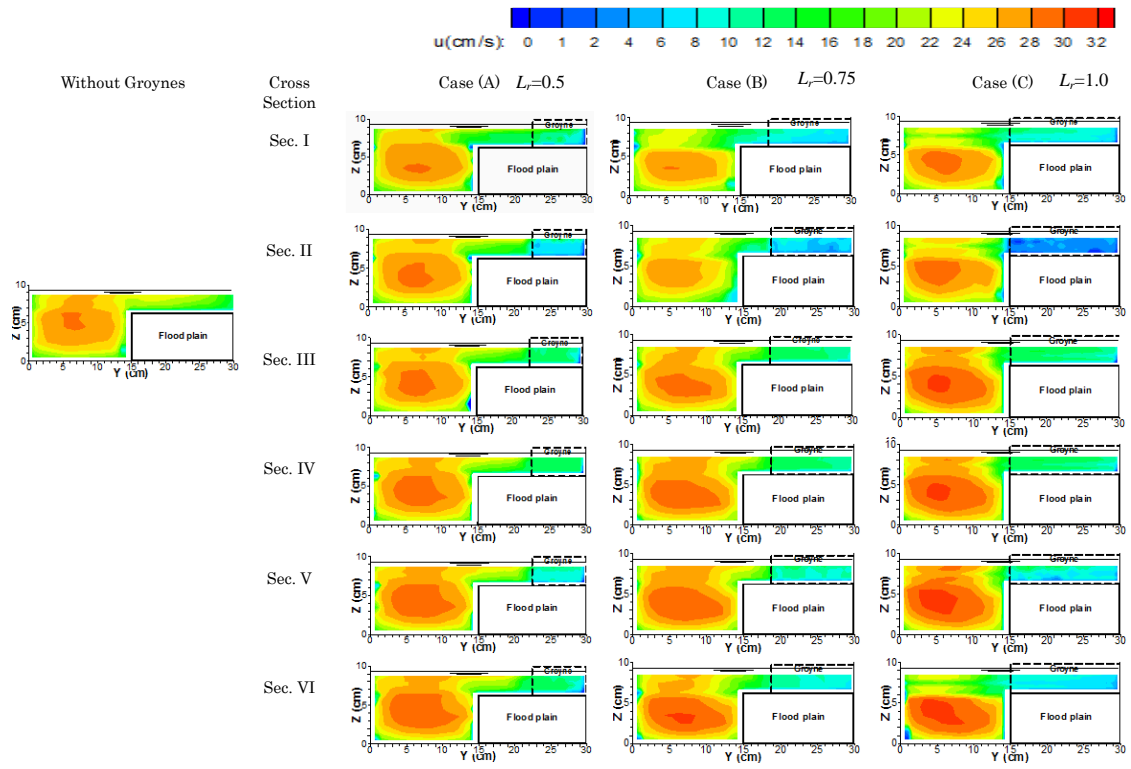


Fig 3

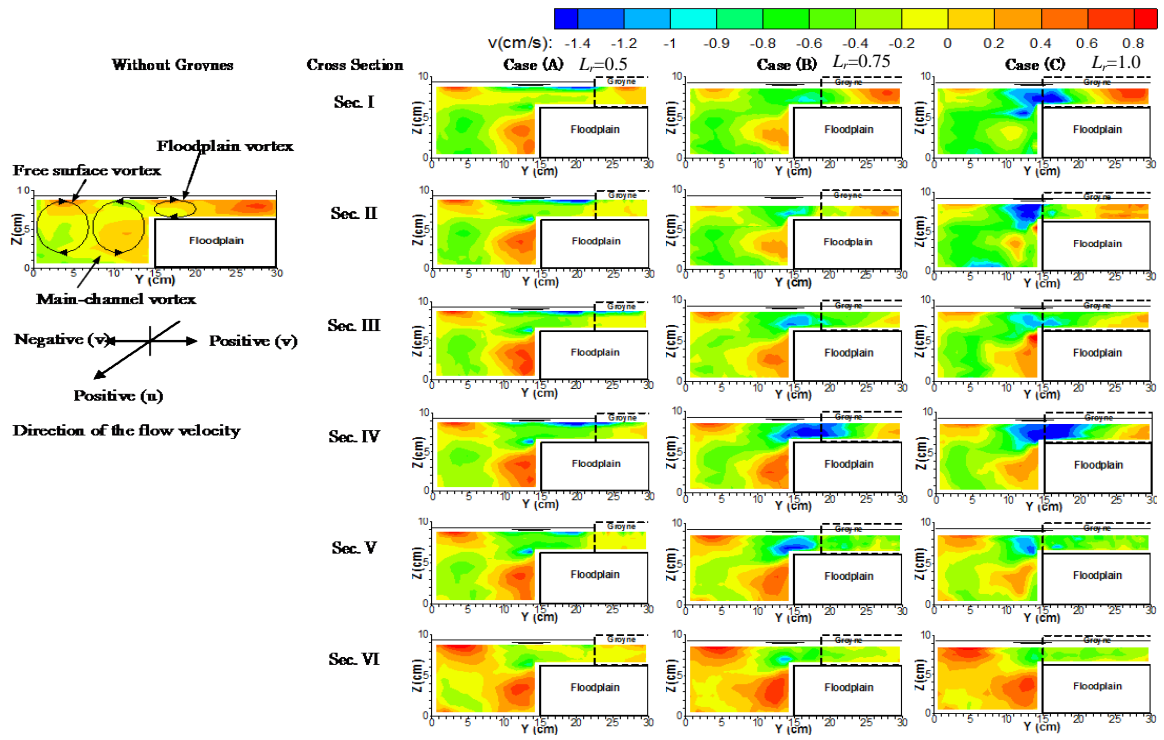


Fig 4

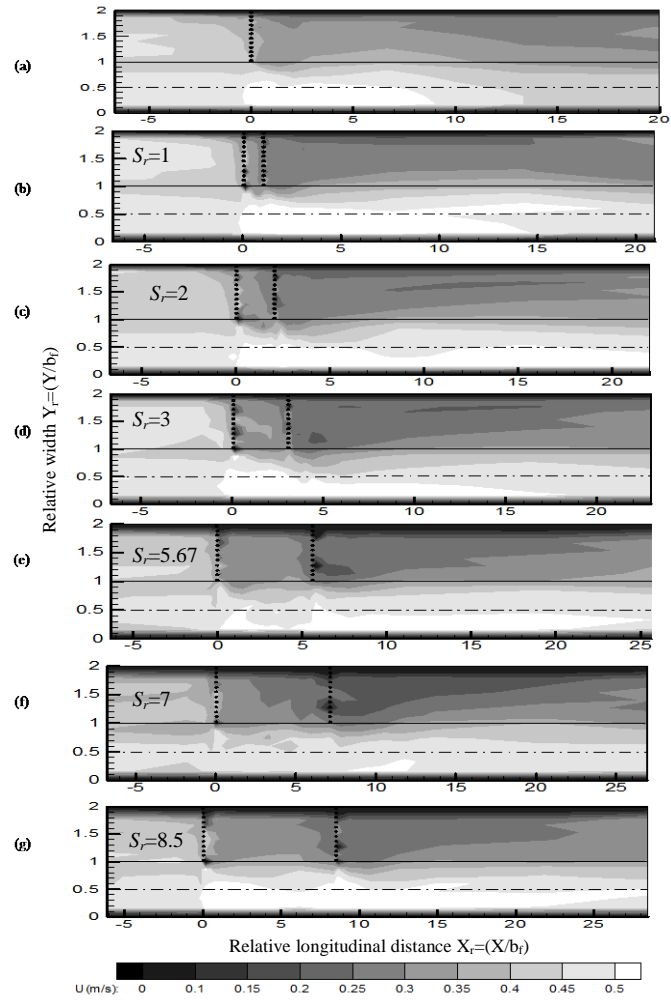


Fig 5

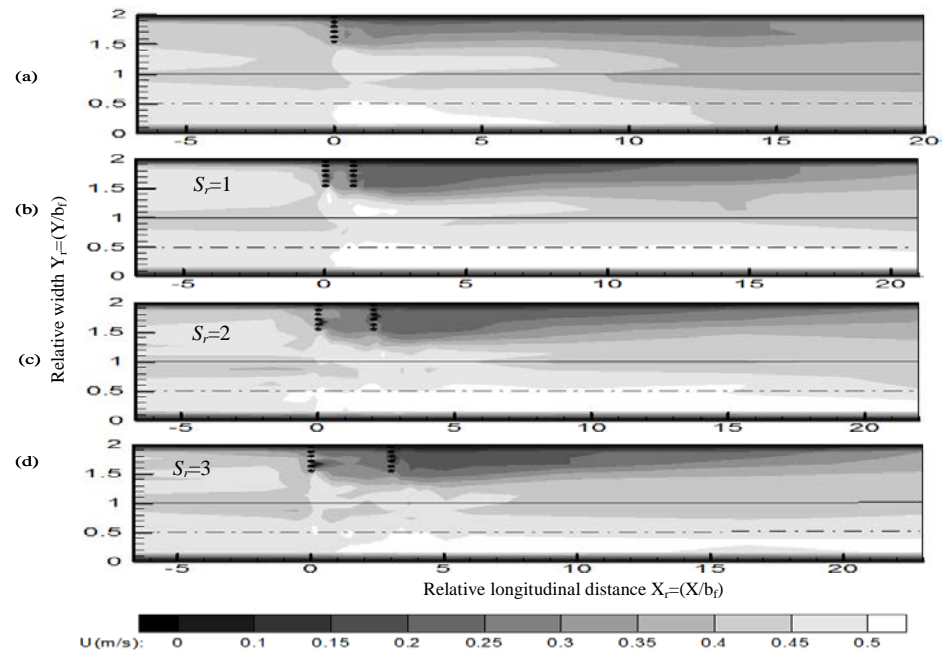


Fig 6

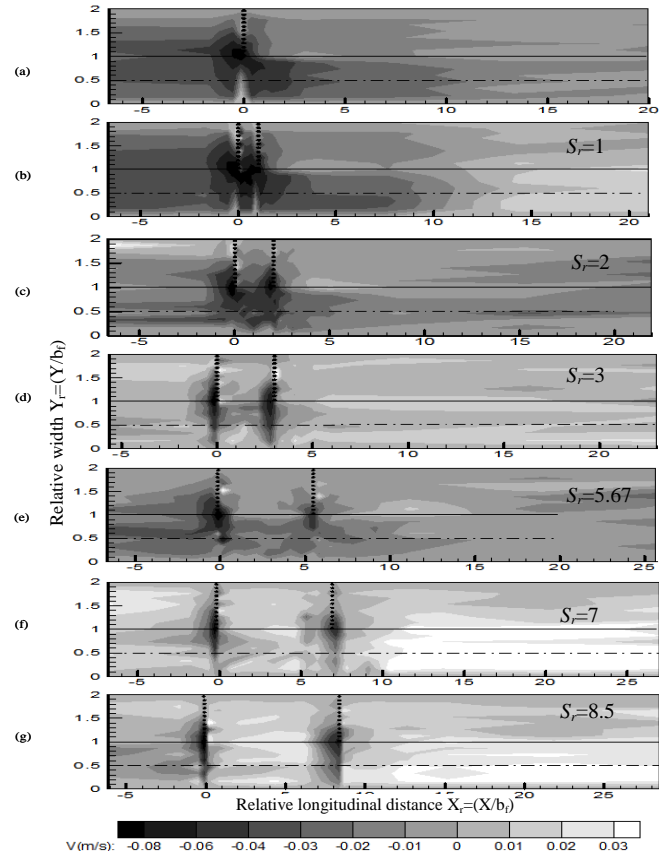


Fig 7

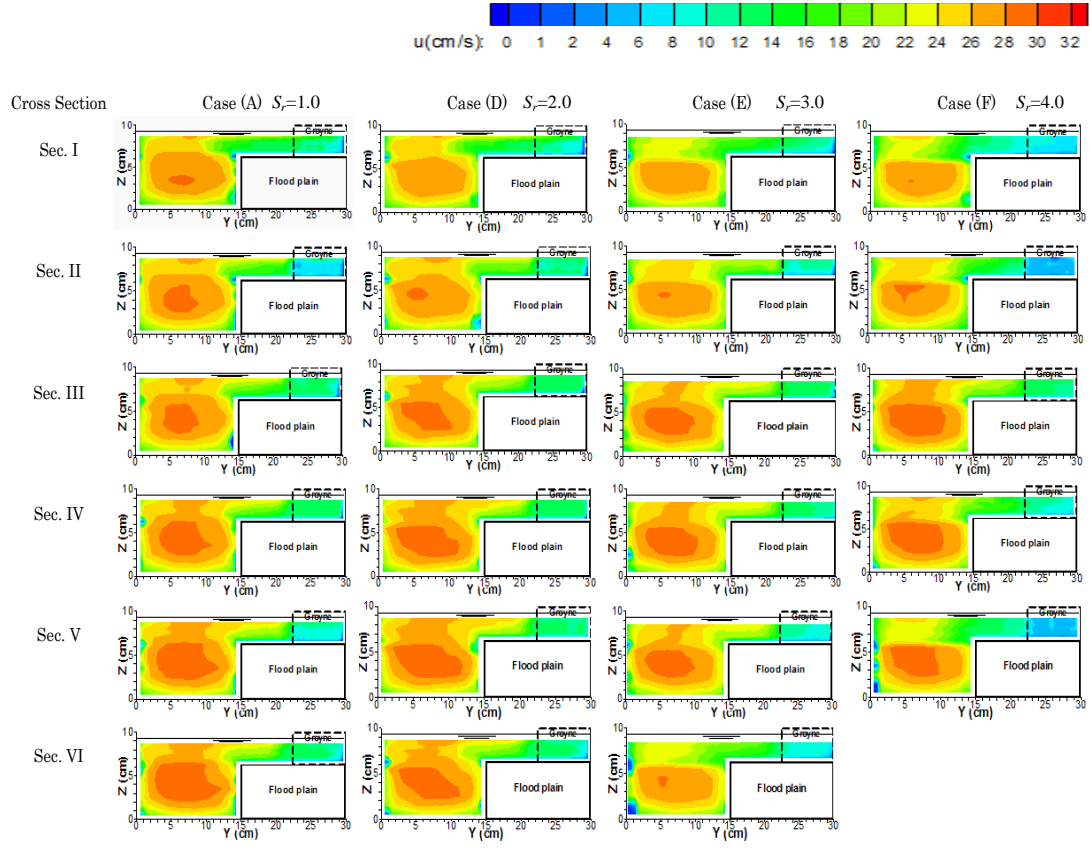


Fig 8

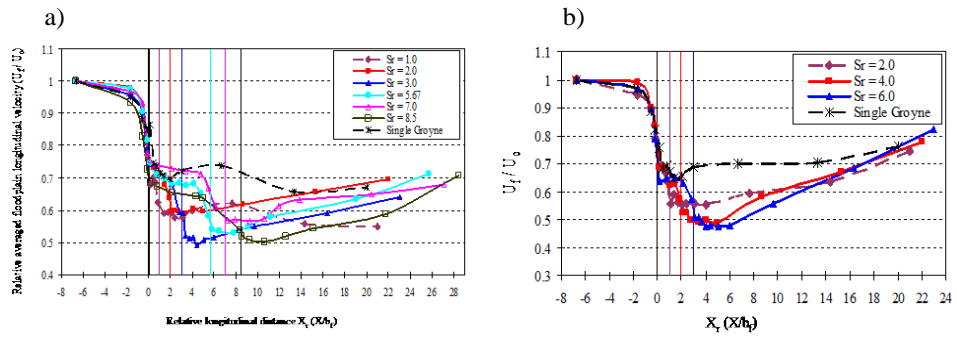


Fig 10

Table 1 The experimental and flow conditions and groynes set up

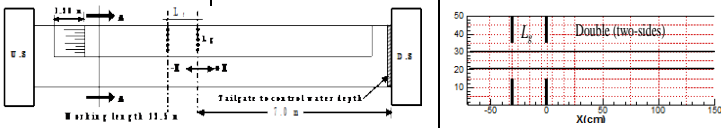
Experiment	Series-I	Series-II	Series-III
Groyne Type	Permeable	Permeable	Impermeable
Compound Channel	Unsymmetrical	Unsymmetrical	Symmetrical
Groyne relative length ($L_r = L_g/b_f$)	0.5, 0.75 & 1	0.5, 0.75 & 1	0.75 & 1
Aspect Ratio ($S_r = L_f/L_g$)	1, 2, 3, 5.67, 7 & 8.5	1, 2, 3 & 4	2, 4, 6 & 8
Velocity Measurement	ADV	PIV	EMV
Flume total width (B)	0.30 m	0.30 m	0.50 m
Main Channel Width (b_m)	0.15 m	0.15 m	0.10 m
Floodplain width (b_f)	0.15 m	0.15 m	0.20 m
Main Channel water depth	0.23 m	0.23 m	0.24 m
Floodplain relative water depth (h_f/H)	0.34	0.32	0.33
Bed Slope (S_o)	0.0025	0.0005	0.0005
Flow (Q)	17.5 l/s	4.14 l/s	15.0 l/s
Froude Number	0.30	0.26	0.26
Flume Arrangements			

Table 2 Location of the measured cross-sections:

Section	Sec. I	Sec. II	Sec. III	Sec. IV	Sec. V	Sec. VI
Positions	Upstream from the first groyne by 2.0 cm	Downstream from the first groyne by 2.0 cm	Mid-distance between the two groynes	Upstream from the second groyne by 2.0 cm	Downstream from the second groyne by 2.0 cm	Downstream from the second groyne by 15 cm

The diagram illustrates the experimental setup with two groynes (1st and 2nd) and the locations of measured cross-sections (Sec. I to Sec. VI). The flow direction is indicated by an arrow labeled 'Flow'. The diagram shows the 'Floodplain' and 'Main Channel' areas. The distances between sections are labeled as follows: Sec. I to Sec. II is 2.0, Sec. II to Sec. III is $L_f/L_g = 0.5$, Sec. III to Sec. IV is $L_f/L_g = 0.5$, Sec. IV to Sec. V is 2.0, and Sec. V to Sec. VI is $L_f/L_g = 1.0$. The diagram also shows the '1st Groyne' and '2nd Groyne' locations.

All dimensions are in cm